Effect of Lockdown on HCHO and Trace Gases over India during March 2020

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ABSTRACT

COVID-19 is one of the deadly Epidemics that has impacted people living in more than 200 countries. In order to mitigate the impact of COVID-19, India observed total lockdown in the first phase for a period of 21 days (24 March–13 May 2020), so that social distancing is maintained. However, this sudden decision severely affected the normal life of people. The air quality improved due to lockdown, some relaxation was given in different cities and within some areas in the city where the people were not affected by COVID-19. In this paper, we discuss results of detailed analysis of trace gases (HCHO, NO_2, SO_2, CH_4, CO and O_3) and particulate matter concentration using satellite and ground data in major metropolitan cities of India during 10–31 March, 2020 and compared with the same period in the year 2019, to study the impact of total lockdown. Our analysis suggests, pronounced qualitative changes in HCHO, NO_2, SO_2, CH_4, CO, O_3 and $PM_{2.5}$ concentration during complete lockdown period in the month of March 2020. We did not consider the period after 31 March 2020 to avoid influence of anthropogenic sources since the Government made relaxation in the lockdown periods after 31 March 2020.

Keywords: COVID-19, Trace gases, $PM_{2.5}$, Air quality, HCHO, India

1 INTRODUCTION

The COVID-19 is now known as one of the deadly epidemics of Modern Era (https://www.who.int/news-room/detail/27-04-2020-who-timeline--covid-19). About 37,113,410 people suffer with this epidemic and about 1,072,712 killed in the world (https://www.worldometers.info/coronavirus/), still the number is increasing day by day. The COVID-19 started from Wuhan city, capital of Hubei province of China (Chauhan and Singh, 2020; Rajbhandari *et al.*, 2020; Singh and Chauhan, 2020; Wang *et al.*, 2020a) in the month of December 2019 and the world came to know about this deadly virus in the beginning of 2020. With the increase in the COVID-19 cases, the whole world is moving through a very distressing situation (Wang *et al.*, 2020b, c).

Few cases were reported in India in the beginning of January 2020 which was associated with the Italian tourists and few Indians returning to India from abroad. Looking at the serious nature of the COVID-19, Government of India observed Janata (People's) curfew on 22 March 2020, after its success, the Government of India immediately implemented total lockdown as of 24 March 2020 for 21 days in the first phase (Chauhan and Singh, 2020; Singh and Chauhan, 2020). During this lockdown, improvement in air quality was observed in India. Efforts were made to use ground air quality ($PM_{2.5}$, PM_{10}, CO, NO_2, SO_2, O_3) from the Central Pollution Control Board (CPCB) data and improvement in air quality in different cities, different states and in whole of India, was observed (Mittal *et al.*, 2012; Kumari and Toshniwal, 2020; Mahato *et al.*, 2020; Selvam *et al.*, 2020; Sharma *et al.*, 2020). Chauhan and Singh (2020) and Singh and Chauhan (2020) used air quality data from the sensors deployed in five U.S. embassies in India, the data are freely available through the U.S. EPA (Environmental Protection Agency), a pronounced improvement in air quality was observed.

In the present study, we have analysed trace and greenhouse gases over India, and major metropolitan cities in India during March 2019 and 2020 using satellite data. During lockdown periods, the major anthropogenic sources were minimum, so we considered analysis of these gases to get a clear picture of the atmospheric chemistry during complete lockdown period. We have considered an average of 10–21 March prior and during lockdown periods 22–31 March 2020 and compared with the same time periods for the year 2019. We did not consider the period after 31 March 2020 to avoid influence of anthropogenic sources since the Government made relaxation in the lockdown periods after 31 March 2020.

1.1 Lockdown in India during COVID-19

During COVID-19, partial to total lockdown was observed in some of the severely affected cities/states of various countries around the world, in India, a complete lockdown was strictly followed. Wang *et al.* (2020d) have shown a decline in $PM_{2.5}$ concentration in major cities of China during lockdown due to reduction in traffic on the roads. Chauhan and Singh (2020) observed decline in $PM_{2.5}$ over major cities of the world and major cities in India where US embassies are located (Singh and Chauhan, 2020). Recently, Sharma *et al.* (2020) have used Central Pollution Control Board data and studied the impact of air quality for the periods 15 March−14 April 2020. Lockdown affected all social and economic activities in India and even the river quality of water has been found to be cleaner (Garg *et al.*, 2020).

In India, beginning from April, each year, wheat, and sugarcane crops are harvested, and farmers start making sugarcane by-products, these are the sources of atmospheric pollution and cause poor air quality. Government of India exempted farmers in the villages during the lockdown period after first week of April 2020, for the harvesting of crops. Emergency services and telecom sectors were also exempted during the lockdown. Later, the lockdown was extended further until 3 May 2020 and beyond. Due to lockdown in India, most of the sources associated with the anthropogenic were completely stopped in the first phase. Even the trains and flights (domestic and international) were stopped. Pronounced decline in consumption of fossil fuel was noticed (https://www.businesstoday.in/sectors/energy/lockdown-impact-indian-fuel-consumption-drop-60-in-april/story/401318.html). Due to improvement of air quality, visibility in many cities was improved significantly. Recently, Gupta *et al.* (2020) have analysed various kinds of weather data and predicted model for spread of COVID-19 in U.S. and India.

1.2 Major Sources of Atmospheric Pollution

The northern parts of India especially in the Indo-Gangetic Plain (IGP) is well known as one of the highly polluted and agriculturally productive regions in India. Delhi, capital of India, is located in the IGP which is known as one of the polluted cities in the world, compared to Beijing city in China (Zheng *et al.*, 2017). The sources of pollution, seasonal variability and long term of pollutants are studied by many (Prasad and Singh, 2007; Mittal *et al.*, 2012; Guttikunda *et al.*, 2014; Singh, 2014; Arif *et al.*, 2018; Sarkar *et al.*, 2018a). Lockdown affected most of anthropogenic sources, but some sources remained functional even during lockdown, like, thermal power plants, biomass burning, brick kilns, sugar mills etc. In village, livestock and crop residue burning is quite common for the preparation of food (Smith *et al.*, 1983; Ramachandra *et al.*, 2015; Arif *et al.*, 2018). Lockdown encouraged poor families to burn biomass in rural area so Government of India provided free Liquid Petroleum Gas (LPG) cylinders to economically challenged community under Ujjawala Gas Scheme (https://pib.gov.in/PressReleasePage.aspx?PRID=1614723). Crop residue burning is a major sources of air pollution in India during post-monsoon season in the Northern, Southern and Central parts of India (Mittal *et al.*, 2009; Singh and Kaskaoutis, 2014; Chauhan and Singh, 2017; Sarkar *et al.*, 2018a, b) and also some activities are observed during pre-monsoon months. This is one of the major sources of various trace gases such as CO_2, CO, NO_x, CH_4, and SO_2, and along with this it also emits un-burnt carbon into the atmosphere. According to Streets *et al.* (2003), CRB contributes approximately 0.37 Tg of Sulphur dioxide, 1100 Tg of CO_2, 3.1 Tg of methane CH_4, 2.8 Tg of NO_x, and 67 Tg of CO. India is one of the second largest (25.2%) contributors to the emission of non-methane Volatile organic compounds (NMVOCs) after China (35.2%), from possible sources such as, residential combustion, increasing traffic emissions and growing industrial emissions (Li *et al.*, 2014; Chutia *et al.*, 2019). Volatile organic compounds (VOCs) are

produced in the atmosphere from both natural and anthropogenic sources and play an important role in the atmospheric chemistry, air quality and climate (Seinfeld and Pandis, 2006; Chutia *et al.*, 2019). Ghosh *et al.* (2015) carried out measurements in Kolkata and observed seasonal variations in HCHO and trace gases and observed very high influence of seasonal wind patterns. In the last three decades, the land use and land cover patterns have grown in the rural and urban areas that have enhanced the VOC emissions. High level of VOCs are from the megacities (Delhi, Mumbai, Kolkata) (Talapatra and Srivastava, 2011; Ghosh *et al.*, 2015). The small petrochemical and coal processing industries, sewage plants and forest fires are the sources of HCHO and mixing ratio in the atmosphere (Dasgupta *et al.*, 2005; Karar and Gupta, 2006; Ghosh *et al.*, 2015). The people living in the cities having high HCHO and VOCs environment have higher risk of cancer especially in Kolkata (Majumdar *et al.*, 2011).

In the north-eastern regions (NER) of India, often times forest fires occur during February and March, that cause poor air quality and atmospheric pollution (Badarinath *et al.*, 2009). In this region, few part of the forest are burnt during March every year for preparation of monsoon crop (https://earthobservatory.nasa.gov/images/85500/fire-in-northeast-india). The agricultural activities, biomass-burning, crop residue burning, brick kilns, oil and gas fields significantly contribute to the atmospheric pollution and poor air quality (Sahu *et al.*, 2015; Pathak *et al.*, 2016; Gogoi *et al.*, 2017). The atmosphere over the Bay of Bengal (BoB) region are polluted due to continental out flow from the industrial coastal and NER regions especially during winter season (Ojha *et al.*, 2012; Kumar and Verma, 2016; Verma *et al.*, 2017; Priyadharshini *et al.*, 2018). Long range transport of dust from the Arabian Peninsula and the Thar desert impact the northern parts of India, especially the Indo-Gangetic Plains (IGP) during the pre-monsoon months. The westerly winds depending upon the wind speed, the dust air mass reaches even in the eastern parts of IGP and beyond affecting a large population, about 900 million people living in the region (Middleton, 1986; Bhattacharjee *et al.*, 2007; Singh, 2014; Kumar *et al.*, 2015; Priyadharshini *et al.*, 2018, 2019; Sarkar *et al.*, 2019).

Atmospheric chemistry plays important role in major atmospheric conditions that is responsible for climatic changes. Gases like CH_4, CO, $NO_2 + NO_x$, SO_2, CO_2, HCHO etc. are important gases that play important role in atmosphere. Some of these gases, CH_4, CO, NO_2 and SO_2 are produced from the anthropogenic activities as a direct product and HCHO is one of the major intermediate products of CH_4 cycle produced from various photochemical oxidation of hydrocarbons and higher aldehydes (Goldan *et al.*, 2000; Singh *et al.*, 2000; Miller *et al.*, 2008). Compared to natural sources, anthropogenic sources cause emission of HCHO which can be harmful for the human beings (WHO, 1999; U.S. EPA, 2003; Dasgupta *et al.*, 2005; Karar and Gupta, 2006). In atmosphere, the life span of CH_4 is few years, CO in months, SO_2 in weeks and NO_2 in day but HCHO is life of few hours (Burkholder *et al.*, 2015), that is decomposed into CO and H_2 in the presence of sunlight. In urban atmosphere, HCHO reacts with OH and HO_2. The night-time losses are slow, and it mainly reacts with nitrate radical. It plays a major role since it acts as a precursor for ozone in the atmosphere. Similarly, CH_4 and NO_2, together helps in formation of CO and are responsible for the formation of surface ozone. Surface ozone is greenhouse gas and can be a major threat to human health. These chemical reactions are as follows (Wallace and Hobbs, 2006; Zheng *et al.*, 2017).

$$OH + CH_4 = H_2O + CH_3 \tag{1}$$

$$OH + CO = H + CO_2 \tag{2}$$

$$OC + CO = H_2O + CH_3CO \tag{3}$$

The radical CH_3, H and CH_3CO involved in reaction which converts NO to NO_2 and regenerate OH. During this reaction HCHO is also produced.
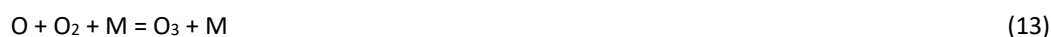
$$CH_3 + O_2 = CH_3O_2 \tag{4}$$

$$CH_3O_2 + NO = CH_3O + NO_2 \tag{5}$$

$$CH_3O + O_2 = HCHO + HO_2 \tag{6}$$

$$HO_2 + NO = NO_2 + OH \tag{7}$$

Further,

$$HCHO + h\upsilon = H + HCO \tag{8}$$

$$HCO + O_2 = HO_2 + CO \tag{9}$$

together with CO and NO is responsible for the formation of ozone at ground level.

$$OH + CO + O_2 = HO_2 + CO_2 \tag{10}$$

$$HO_2 + NO = OH + NO_2 \tag{11}$$

$$NO_2 + h\upsilon = NO + O \tag{12}$$

$$O + O_2 + M = O_3 + M \tag{13}$$

The atmospheric chemistry changes in the presence of sun, and the surface ozone is formed.

1.3 Data Used

In the present study, we have carried out analysis of total column formaldehyde (HCHO), nitrogen dioxide (NO_2), methane (CH_4), carbon monoxide (CO), total column sulphur dioxide (SO_2) and ozone (O_3) using various satellite data.

1.4 Meteorological Data

We have carried out analysis of the meteorological parameters (air temperature, station pressure, and relative humidity) using Airport station data available through https://rp5.ru/Weather_in_the_world.

1.5 AIRS Data

We have considered methane (CH_4), carbon monoxide (CO) and ozone (O_3) gas emissions data observed from the Atmospheric Infrared Sounder (AIRS) for detailed analysis. This data is available at different pressure levels and we have used data at pressure level 925 hPa close to the earth's surface, average of daytime (ascending mode) and night time (descending mode) data for better temporal coverage to avoid gap in data during day or night time. Satellite data (spatial resolution of $1° \times 1°$) is taken through NASA Giovanni portal (https://giovanni.gsfc.nasa.gov/giovanni/).

1.6 OMI Data

The Ozone Monitoring Instrument (OMI) provides information of atmospheric aerosols properties. This instrument provides information about various atmospheric gases, NO_2, ozone and SO_2. This satellite is part of NASA Aura satellite mission which is an A-train satellite. The analysis of atmospheric concentration of HCHO, tropospheric NO_2 and column amount SO_2 (Planetary Boundary Layer) were carried out using OMI AURA data. The resolution of tropospheric NO_2 and column amount SO_2 is $0.25° \times 0.25°$ and for HCHO the resolution of data is $0.1° \times 0.1°$ and is taken from NASA Giovanni portal.

1.7 PM$_{2.5}$ Data

U.S. Environmental Protection Agency (U.S. EPA) provides air quality data of various ground stations across the globe. Air quality ($PM_{2.5}$) data of various cities outside U.S. is available through U.S. EPA AirNow platform (https://www.airnow.gov/international/us-embassies-and-consulates/). The air quality sensors are located in five U.S. Embassies in India, Delhi, Mumbai, Chennai, Hyderabad, and Kolkata (Fig. 1, coordinates of U.S. Embassies are given in Table 1).

For satellite data, we have considered five $1° \times 1°$ boxes (coordinates are given in Table 2) over U.S. embassies in India.

2 RESULTS AND DISCUSSION

2.1 Meteorological Parameters of Major Cities

Fig. 2 shows the temporal variations of meteorological parameters (a) air temperature, (b) relative humidity, and (c) station level pressure. A gradual rise in temperature is observed at all five
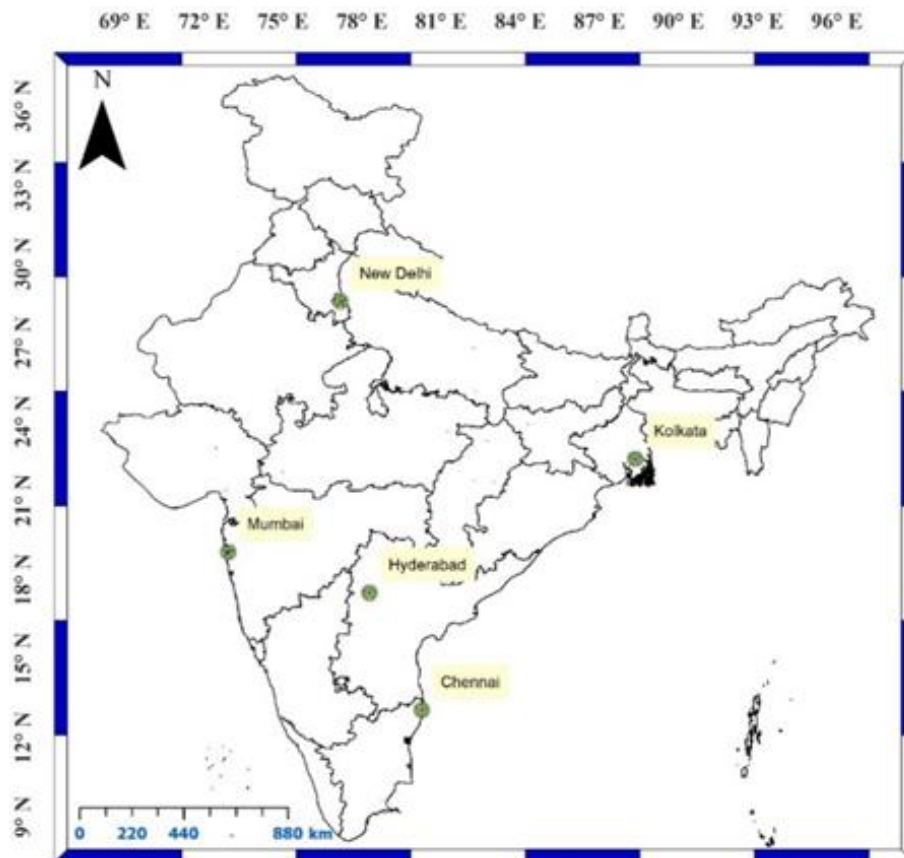

Fig. 1. Location of five embassies in India (green dots).

Table 1. Coordinates of Bounding Boxes ($1° \times 1°$) over five US Embassies.

Station Name	West	South	East	North
Delhi (28.57, 77.18)	76.68	28.07	77.68	29.07
Hyderabad (17.51, 78.28)	77.78	17.01	78.78	18.01
Chennai (13.06, 80.16)	79.76	12.56	80.76	13.56
Mumbai (19.05, 72.92)	72.42	18.55	73.42	19.55
Kolkata (22.58, 88.36)	87.86	22.08	88.86	23.08

Table 2. Coordinates of Bounding Boxes ($1° \times 1°$) over five US Embassies for satellite data.

| Parameter	Source	Spatial Resolution	Temporal Resolution
CH_4 Concentration at 925 hPa	AIRS Satellite Data	$1° \times 1°$	1 Day
CO Concentration at 925 hPa	AIRS Satellite Data	$1° \times 1°$	1 Day
O_3 Concentration at 925 hPa	AIRS Satellite Data	$1° \times 1°$	1 Day
Tropospheric NO_2	OMI Satellite Data	$0.25° \times 0.25°$	1 Day
Column Amount SO_2 (PBL)	OMI Satellite Data	$0.25° \times 0.25°$	1 Day
Column Amount HCHO	OMI Satellite Data	$0.1° \times 0.1°$	1 Day
Concentration of $PM_{2.5}$	US EPA Ground Observations	None	1 hour
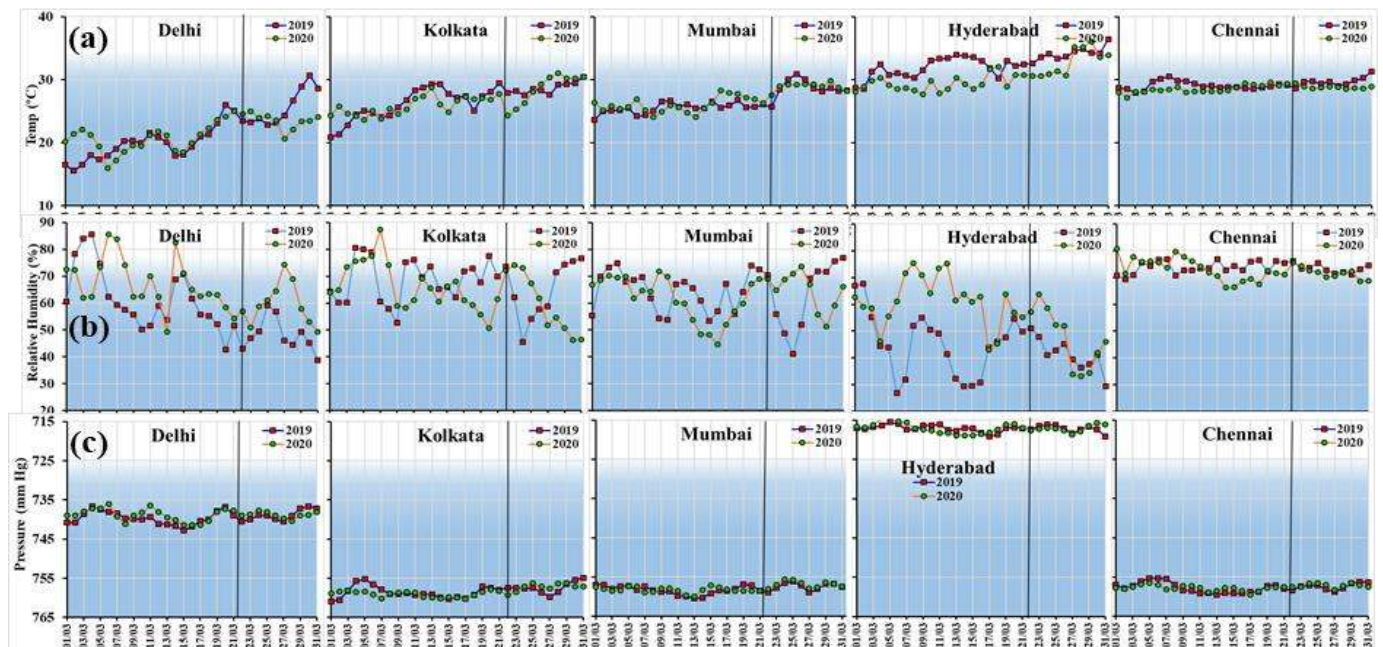
Fig. 2. Temporal variations of (a) Air Temperature, (b) Relative Humidity and (c) Station Level Pressure at five locations during March 2019 and 2020, vertical solid black line is the start date of total lockdown.

locations (Delhi, Kolkata, Mumbai, Hyderabad, and Chennai) during March 2019 and 2020. At Delhi, the average temperature during March 2019 and 2020, respectively, was 21.65°C and 21.54°C. We observed small decline in the average temperature in 2020 after the 22 March and hence the average temperature during 22 March to 31 March 2020 is lower during the same period compared in the year 2019. No major changes are observed with air pressure during 2019 and 2020 over Delhi. The average relative humidity during March 2020 was observed to be higher over Delhi compared to 2019. In Kolkata, no major changes are observed in air temperature, however, the relative humidity is found to be lower over Kolkata during 2020 compared to 2019. Similar changes are also observed over Mumbai, but no major changes are observed in the average temperature at different pressure levels. A decline is found in relative humidity (more than 10%) after 25 March 2020. In Hyderabad, 2°C decline in air temperature is observed in 2020 compared to 2019, however, no changes are observed at different pressure levels. The average relative humidity is observed to be higher in the month of March 2020 during lockdown periods. In Chennai, no major changes are observed in the air temperature, and relative humidity at different pressure levels. The air temperature and relative humidity are observed to be higher, likely due to proximity with the Bay of Bengal. The relative humidity shows variations in 2020 compared to 2019. In 2019, RH shows enhancement over Mumbai and Kolkata after 22 March, a decline in RH is observed during lockdown period in 2020 (Fig. 2(b))

2.2 Daily Variations of $PM_{2.5}$ during March 2019 and 2020

Fig. 3 shows daily variations of $PM_{2.5}$ over Delhi, Hyderabad, Chennai, Mumbai, and Kolkata in the month of March 2019 and 2020. The $PM_{2.5}$ concentrations is observed to be highest in Delhi (62.98 µg m^{-3}), followed by Kolkata (61.99 µg m^{-3}), Mumbai (49.71 µg m^{-3}), and Hyderabad (37.54 µg m^{-3}) during March, whereas, in Chennai $PM_{2.5}$ is lowest (20.57 µg m^{-3}) (Table 3). In comparison to 2019, the average $PM_{2.5}$ concentration is lower in almost all cities during 2020 except in Chennai. In Delhi, Hyderabad, Mumbai, and Kolkata, a pronounced decline in $PM_{2.5}$ concentrations is observed during lockdown period (after 25 March) during 2020. In Chennai, $PM_{2.5}$ is higher in some days in the month of March 2020, the average concentration prior and during the lockdown show a decline in all the five cities. The concentrations of $PM_{2.5}$ depend on the local emissions, depending on the airmass reaching at these five locations. The air quality in Delhi and Kolkata located in the Indo-Gangetic plains (IGP) is generally poor (Sarkar *et al.*, 2018a, 2019; Chauhan and Singh, 2020; Singh and Chauhan, 2020).
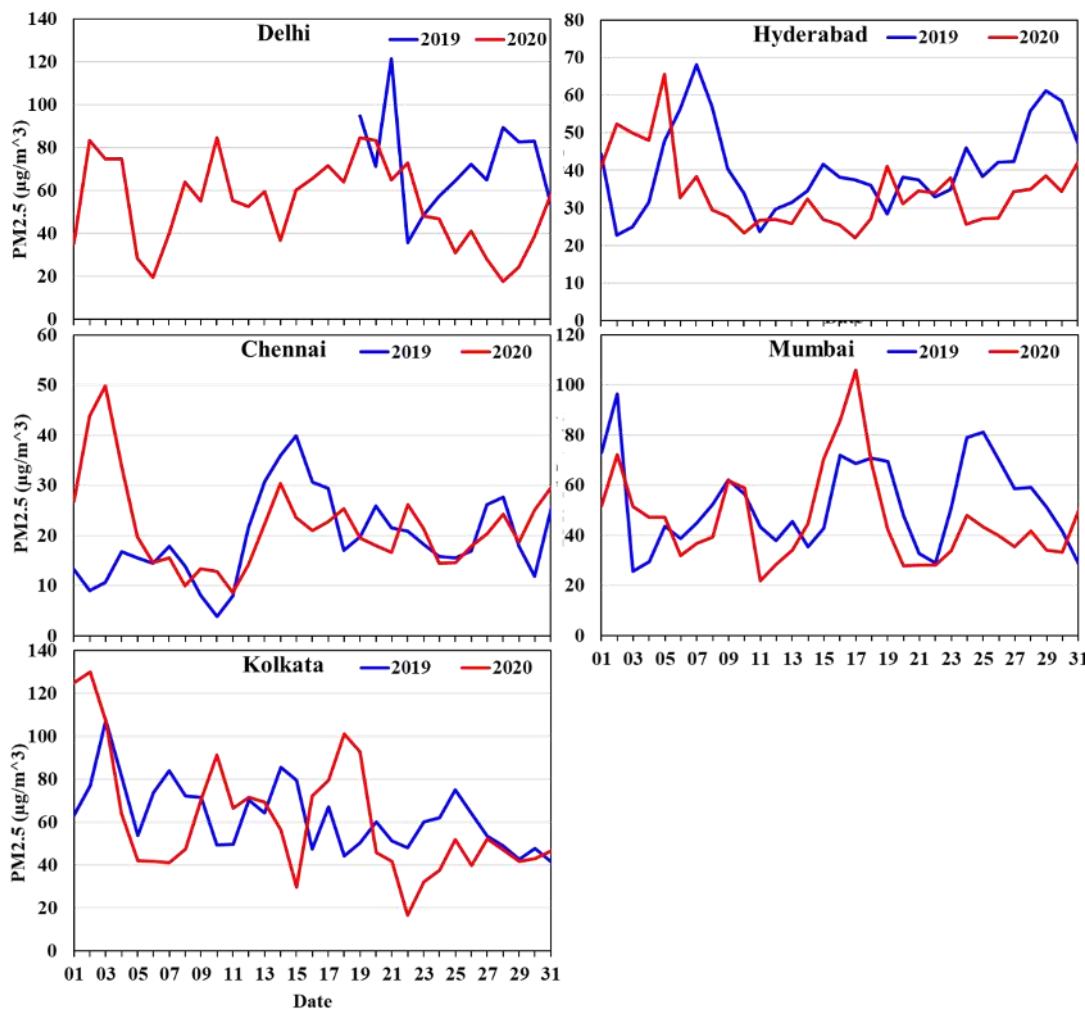
Fig. 3. Daily variations of PM$_{2.5}$ in the month of March 2019 (blue line) and 2020 (red line) at five locations.

The westerly winds influence PM$_{2.5}$ concentrations in Delhi and Kolkata and the southerly and south-easterly winds also impact PM$_{2.5}$ of Kolkata. The PM$_{2.5}$ in Delhi and Kolkata is also affected from long range transport of airmass associated with westerly winds and often due to western disturbances especially in the month of March (Dimri and Chevuturi, 2016). Depending upon the intensity of western disturbances the weather conditions over Delhi and beyond are impacted even up to Kolkata.

In Mumbai and Hyderabad, air quality is mainly affected from local traffic and from airmass reaching from different directions depending upon the wind directions. The PM$_{2.5}$ concentrations in Chennai is variable due to its proximity to the ocean where airmass reaches from all the directions. The PM$_{2.5}$ concentration is of dynamic in nature depends on the wind directions and moistures from the coastal areas. Recently, Singh and Chauhan (2020) have discussed decline in air quality at these five locations in view of the airmass reaching at these locations from different directions and have discussed the change in sources of airmass influencing PM$_{2.5}$ concentrations. The decline in PM$_{2.5}$ compared to 2019 during pre and during lockdown periods is given in Table 3.

2.3 Spatial Variations of HCHO over India

During lockdown period 22–31 March 2020, concentration of various trace gases in atmosphere and other chemical species were reduced due to closure of industrial, vehicular and anthropogenic activities. Fig. 4 shows the average HCHO concentration over India during (a) 10–21 March 2019; (b) 10–21 March 2020; (c) 22–31 March 2019 and (d) 22–31 March 2020. In many parts of India, enhancement in HCHO concentration was observed during 22–31 March 2020 due seasonal increase in temperature. Due to westerly airmass, the temperature of the northern and north-eastern

Table 3. PM$_{2.5}$ (μg m^{-3}) concentration over five major cities.

Year	2019 (Avg)	2020 (Avg)	2019 (Std)	2020 (Std)
Delhi				
March	72.27	53.68	22.44	20.20
Before 25 March	71.48	59.40	31.83	18.32
After 25 March	72.96	34.08	12.71	13.17
Hyderabad				
March	40.73	34.34	11.41	9.71
Before 25 March	38.20	34.42	10.90	10.74
After 25 March	49.40	34.09	9.06	5.46
Chennai				
March	19.35	21.79	8.47	8.99
Before 25 March	19.11	21.88	9.15	9.93
After 25 March	20.17	21.50	6.09	5.11
Mumbai				
March	52.85	46.58	17.88	18.69
Before 25 March	51.99	48.60	18.28	20.68
After 25 March	55.77	39.67	17.45	5.93
Kolkata				
March	62.82	61.15	15.45	27.82
Before 25 March	65.57	65.55	15.45	30.22
After 25 March	53.42	46.06	12.06	4.91

parts of India remain lower, whereas, due to higher temperature in the southern and south eastern parts of India, higher concentration of HCHO was observed in the southern and south-central India. Lower concentration of HCHO is observed in the northern, western, and north-western parts of India as temperature is comparatively lower during March. Higher concentration areas are also observed in the north-eastern parts due to forest fires and biomass burning. A decline in the concentrations was observed in 2020 compared with the same periods in the year 2019.

The HCHO concentration was observed to be higher during 22–31 March 2019 (Figs. 3(a) and 3(c)). An enhancement in HCHO corresponds to rise in temperature and crop burning activities. During March 2020, due to lockdown, absence, or lower density of road traffic, industrial emissions and crop burning activities, HCHO concentration decreased in the northern, western, and north-western parts during 22–31 March 2020 even after rise in temperature. In central, southern, and south-central parts of India, the average concentration is observed to be smaller compared to 2019. So, the effect of lockdown is clearly visible qualitatively during 2020.

We have carried out the analysis of average concentration of column amount HCHO over five major cities of India during (a) 10–21 March, 2019; (b) 10–21 March, 2020; (c) 22–31 March, 2019 and (d) 22-31 March, 2020 (Fig. 5). In Delhi, the average concentration is observed to be higher during 10–21 March, compared to 22–31 March in both the years. Even highest HCHO concentration is observed during 10–21 March 2020. At the border areas of Delhi, the average concentration was observed to be higher during March this is likely due to the industrial areas located in outer Delhi. The impact of lockdown is clearly observed over Delhi during 22–31 March 2020 since the average concentration is observed to be lower compared to other time periods.

There is no data available during 22–31 March 2019 in the northern parts of Delhi. Kolkata city is in the eastern parts of the Indo-Gangetic Plains and mostly influenced by the westerly airmass during March. An enhancement in HCHO concentration was observed during lockdown periods (after 21 March until 31 March 2020) in Kolkata, whereas, for the same period in 2019, decline in HCHO concentration was observed. In Mumbai, enhancement in HCHO concentration was observed during 22–31 March 2020 compared to 10–21 March 2020. However, when we compared HCHO for the periods 22–31 March 2019, decline in HCHO concentrations was observed during lockdown period over Mumbai. Similar changes are also observed over Chennai, where decline in HCHO concentration was observed during 22–31 March 2020 compared to 22–31 March 2019. However, in later half during March (22–31), HCHO concentration was observed to be higher compared to 10–21 March in 2019 and 2020.
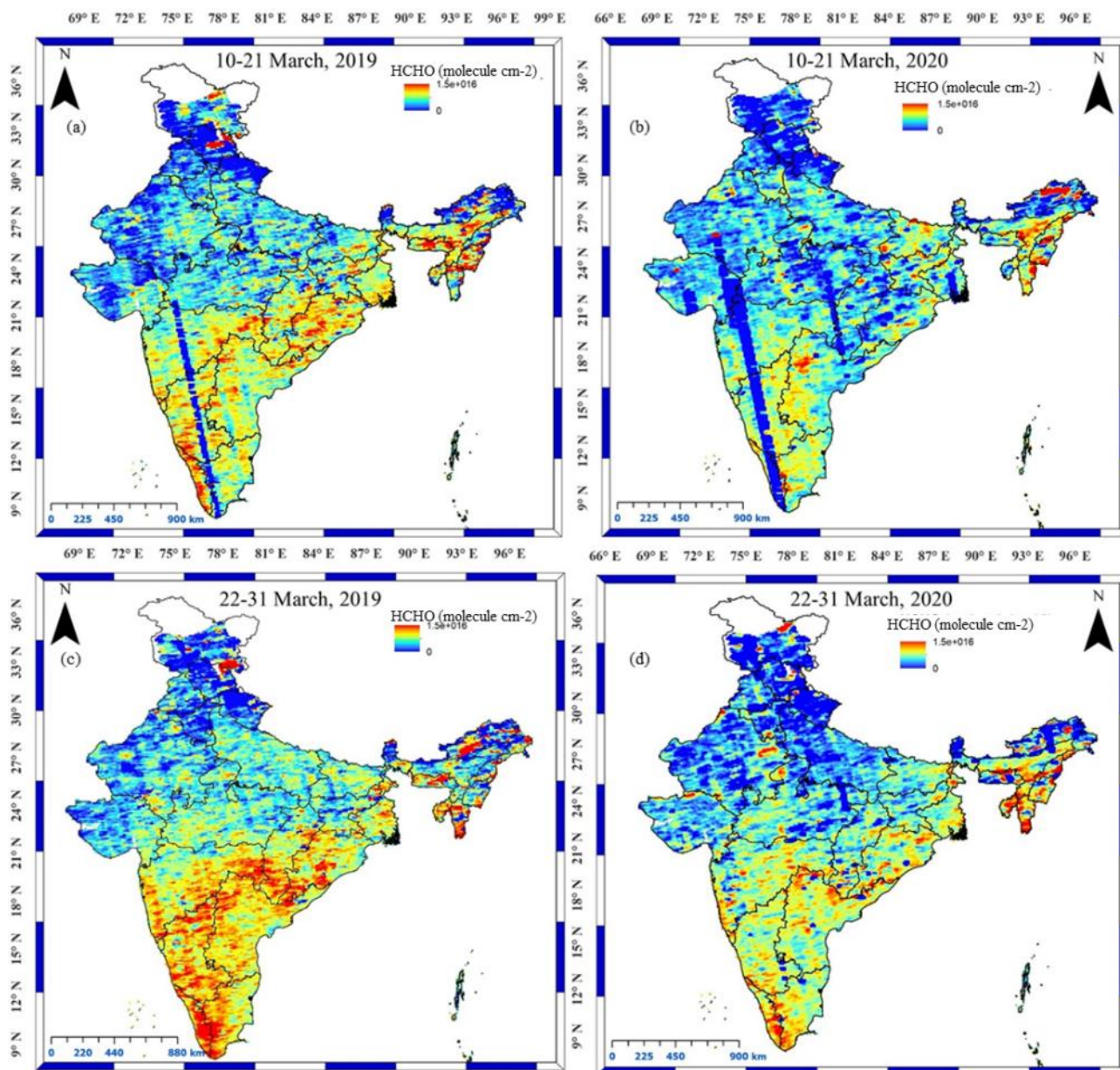
Fig. 4. Spatial variations of column amount of HCHO during (a) 10–21 March 2019; (b) 10–21 March 2020; (c) 22–31 March 2019 and (d) 22–31 March 2020.

In Hyderabad, the average concentration during March 2020 was observed to be higher compared to March 2019, decline in HCHO concentration was observed due to lockdown. We observed effect of temperature and long-range transport showing higher concentration of HCHO over Kolkata, Chennai, and Mumbai. In Delhi and Hyderabad, we found slight decline in HCHO concentration, this could be due to influence of long-range transport of westerly and easterly airmass.

2.4 Tropospheric NO_2

NO_2 is a trace gas and its resident time in troposphere is quite short (few hours) which is considered as one of the important key parameters to account for air quality. Singh and Chauhan (2020) carried out analysis of tropospheric NO_2 over India during (a) 10–21 March 2019; (b) 10–21 March 2020; (c) 22–31 March 2019 and (d) 22–31 March 2020 and found that tropospheric NO_2 hotspots are mostly located in the central parts of India where major sources of NO_2 are located (coal-based power plants) (Prasad *et al.*, 2006, 2012). The tropospheric NO_2 is observed
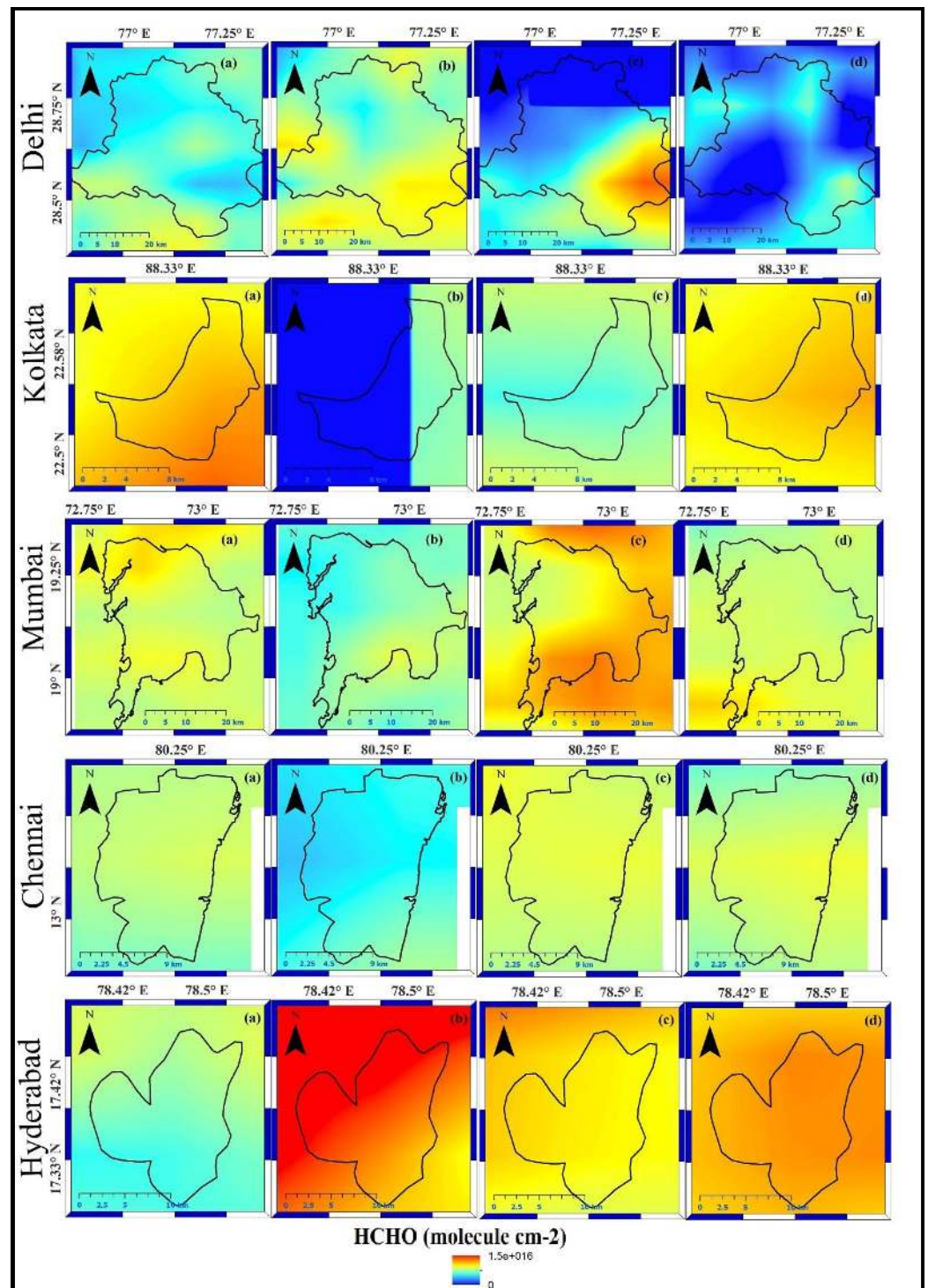
Fig. 5. Spatial average column amount of HCHO over five cities during (a) 10–21 March 2019; (b) 10–21 March 2020; (c) 22–31 March 2019 and (d) 22–31 March 2020.

to be higher in the eastern parts of India where forest fires produce tropospheric NO_2 during March. The total lockdown affected mining activities, thus, NO_2 concentration was observed to be declined over Jharkhand and Odisha. Further, we have carried out analysis of temporal variations of tropospheric NO_2 in major cities of India and compared the results during 2019 and 2020 (Fig. 6). Tropospheric NO_2 is also important due to its role in formation of tropospheric ozone. In Delhi, tropospheric NO_2 is $1.64 \times 10^{+15}$ cm^{-2} during lockdown period 22–31 March 2020 and prior to the lockdown period during 10–21 March 2020 was $4.31 \times 10^{+15}$ cm^{-2}, shows decline
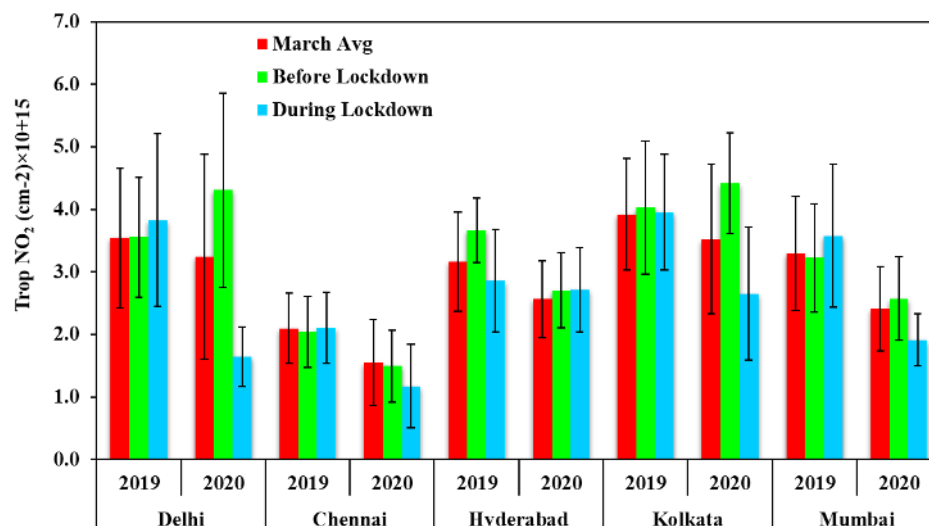
Fig. 6. Average tropospheric NO_2 over five cities during (a) March (red bars); (b) before lockdown (green bars) and (c) during lockdown (blue bars).

in NO_2 concentrations. Decline of 62% is observed in tropospheric NO_2 concentration after the lockdown in Delhi. For the same time in 2019, 8% enhancement is observed in tropospheric concentration in Delhi. In Mumbai, the average concentration during 10-21 March 2020 was $2.57 \times 0^{+15}$ cm^{-2} and later during 22–31 March 2020 it was $1.91 \times 10^{+15}$ cm^{-2}. A total of 26% decline in tropospheric NO_2 concentration is observed in Mumbai. Similarly, in Chennai, a decline of 22% and in Kolkata, 40% is observed during 22–31 March 2020 with respect to 10–21 March 2020. In Hyderabad, no change was observed in NO_2 concentration during lockdown period. The sudden rise in relative humidity is observed during 20–23 March corresponds with sudden rise in air temperature, that may be the cause of higher NO_2 concentration. We have found the average tropospheric NO_2 concentration lower during 2020 at all locations compared to 2019.

2.5 Spatial Distribution of HCHO/NO_2

Using spatial distribution of HCHO (Fig. 4) from OMI AURA data and NO_2 from OMI AURA data from our earlier studies (Singh and Chauhan, 2020), we have computed ratio of HCHO/NO_2 (Fig. 7). The ratio less than 2 represents the NO_2 limited ozone production region and the ratio less than 1, shows the VOC limited ozone production. The ratio between 1–2 represents the transition regime where ozone production is sensitive to both NO_2 and VOC (Duncan *et al.*, 2010; Chutia *et al.*, 2019). During 10–21 March 2019 ozone production is observed to be sensitive to NO_2 in the southern parts of India and in the central, northern, and eastern parts show mostly in transition regime or VOC sensitive, condition is like 2020. During 22–31 March 2019, we observed NO_2 sensitive regions over the western, central and north-eastern parts, mostly in transition regime. During 22–31 March 2020, the western, central, and north-eastern parts shows VOC limited or in transition regions.

2.6 Change in SO_2

In Fig. 8, we have shown the spatial distribution of average SO_2 (planetary boundary layer). During March 2019, higher SO_2 concentration was observed over the central, southern, and western parts of India. The coal mining region of the Jharkhand state (in the eastern parts of the Indo-Gangetic plains) was seen distinctively with higher SO_2 concentration that observed to increase in the southern parts of India during 22–31 March 2019. During 10–21 March 2020, SO_2 concentration was observed to be higher over Jharkhand, Odisha and in the northern parts of India in comparison to 2019. A pronounced decrease in SO_2 concentration was observed during lockdown period 22–31 March 2020 over major parts of India. This time sudden rise in SO_2 concentration was observed over Rajasthan and Punjab (states) (north western parts), but during 2019 it was not observed. The higher SO_2 concentration was observed in this region due to the
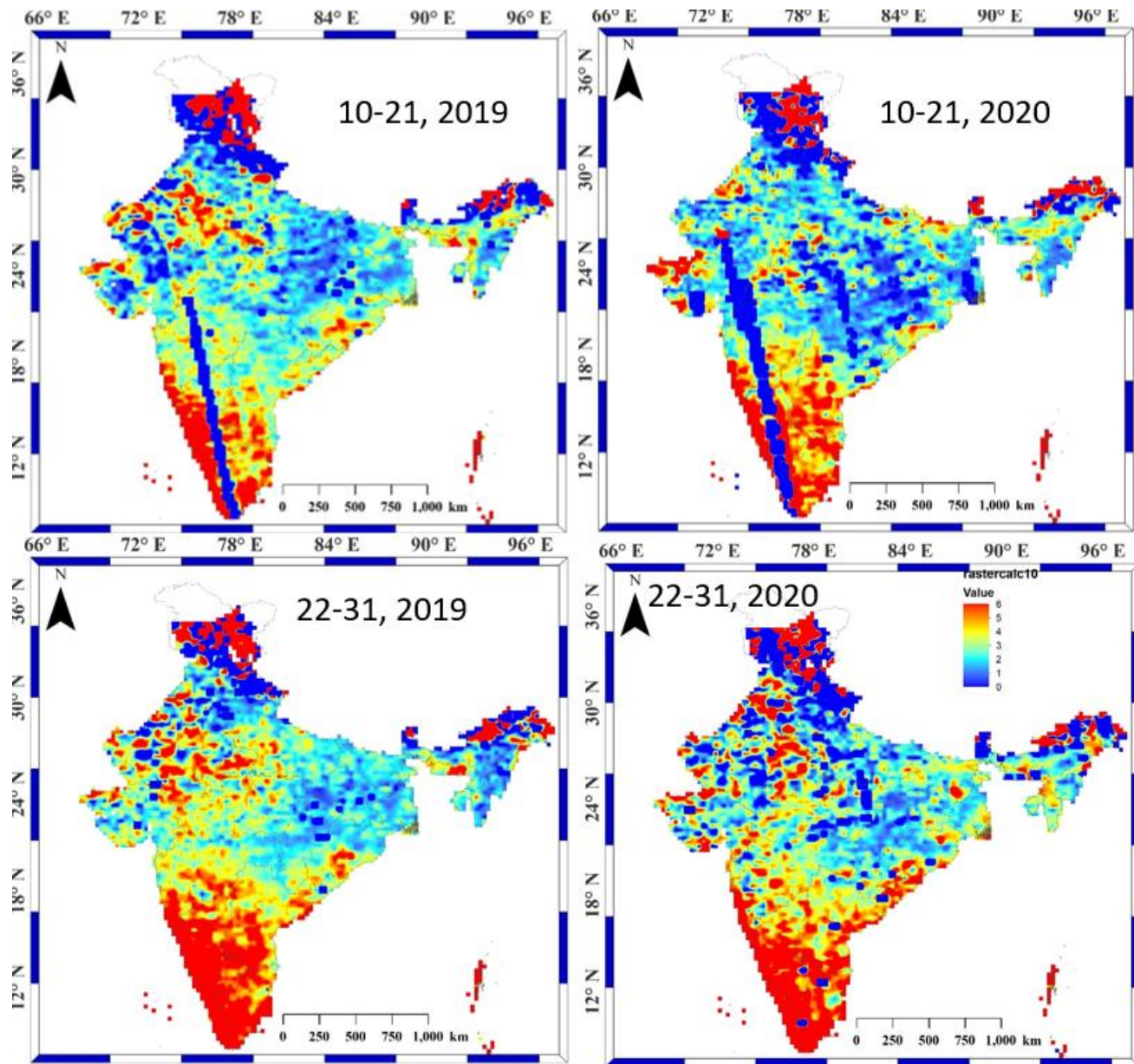
Fig. 7. Spatial distribution of HCHO/NO$_2$ ratio over India during pre (10–21 March 2020 and similar periods in 2019 and during lockdown period 22–31 March 2020 and for the same period in 2019 for comparison.

long-range transport of airmass from Punjab province of Pakistan side associated with the westerly winds.

The SO$_2$ concentration was observed to be higher during March in Punjab province of Pakistan (Khattak *et al.*, 2014) associated with the coal based power plants located in Pakistan.

2.7 Change in Methane Concentration

Methane is one of major greenhouse gases in the atmosphere, next to CO$_2$. We have carried out analysis of methane at 925 hPa (Fig. 9). An enhancement in methane concentration was observed in Delhi and Kolkata and in the Indo-Gangetic plains, whereas decline in methane concentration was observed during lockdown period in 2020 over Hyderabad, Chennai, and Mumbai.

In Delhi, an average methane concentration was observed to be lower (1861 ppbv) during March 2020 compared to March 2019 (1871 ppbv). During 22–30 March 2019, the average concentration was lower with respect to 10–21 March 2019 and in 2020, enhancement was observed in CH$_4$ concentration during lockdown period. In Kolkata, the average concentration as
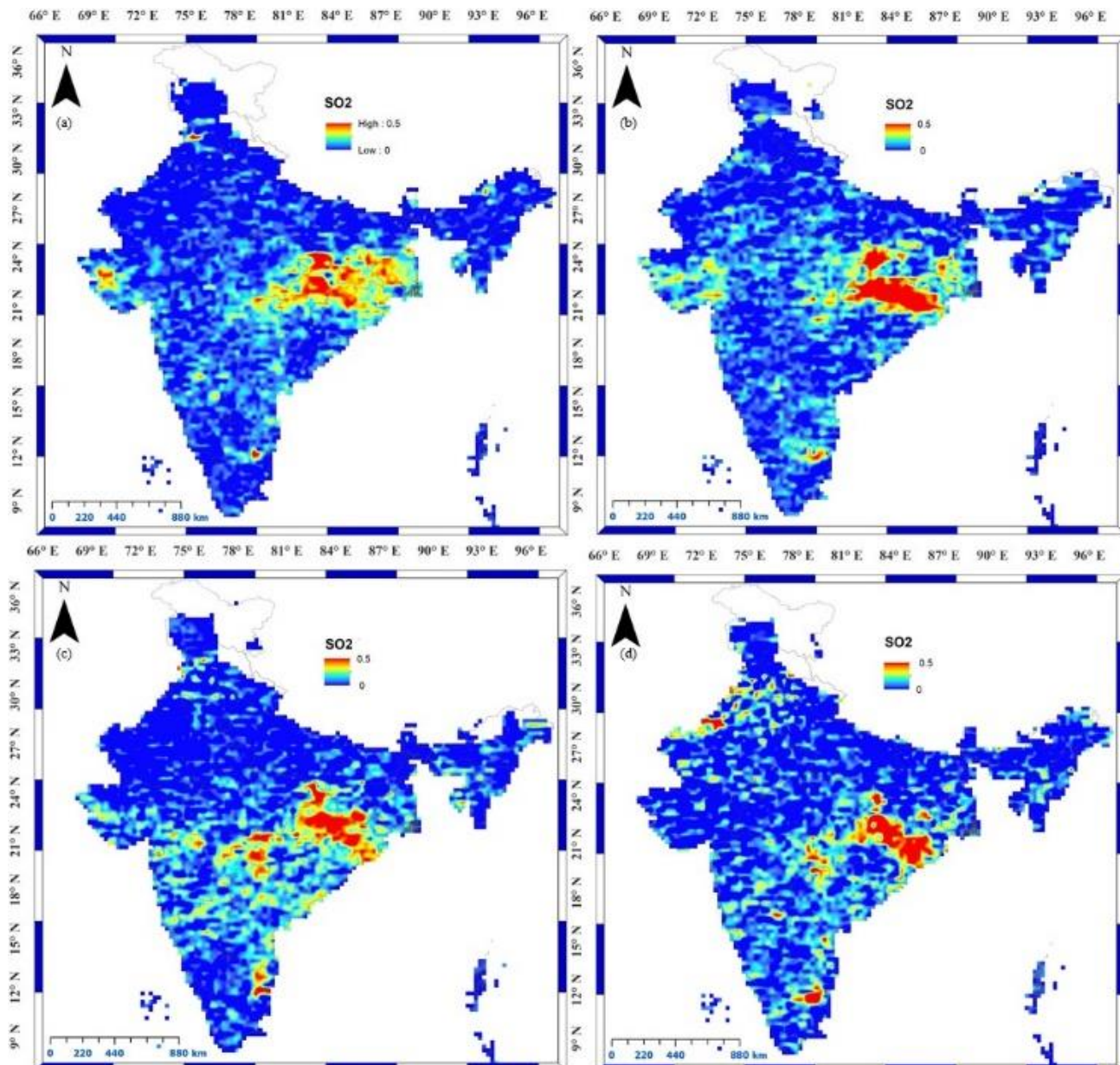
Fig. 8. Spatial variations of SO$_2$ (pbl) over India during (a) 10–21 March 2019; (b) 10–21 March 2020; (c) 22–31 March 2019 and (d) 22–31 March 2020.

well as concentration during lockdown, both are found to be higher compared to 2019 and before lockdown period. In Chennai, average enhancement in methane concentration was observed to be small but after 22 March 2020 concentration was declined. In Hyderabad, decline was observed in the average value of March 2020 compared to 2019 and during lockdown period, sudden decline was observed in methane concentration. In Mumbai, an increase in average concentration was observed during March 2020 but decline in the average concentration during 22–31, March 2020 during lockdown period. The methane concentration shows no major direct relationship with decline in anthropogenic activities due to its longer residential time and emission due natural sources.

In Fig. 10, we have shown the average CO concentration over five major cities of India during March 2019 and 2020. In Delhi, the average CO concentration was higher during March 2020 and decline during the lockdown period. In Chennai, an increase in CO concentration was observed during March 2020 but decline in CO concentration during lockdown period. In Hyderabad, the results are like Chennai city. But in Kolkata the average CO concentration was like those during
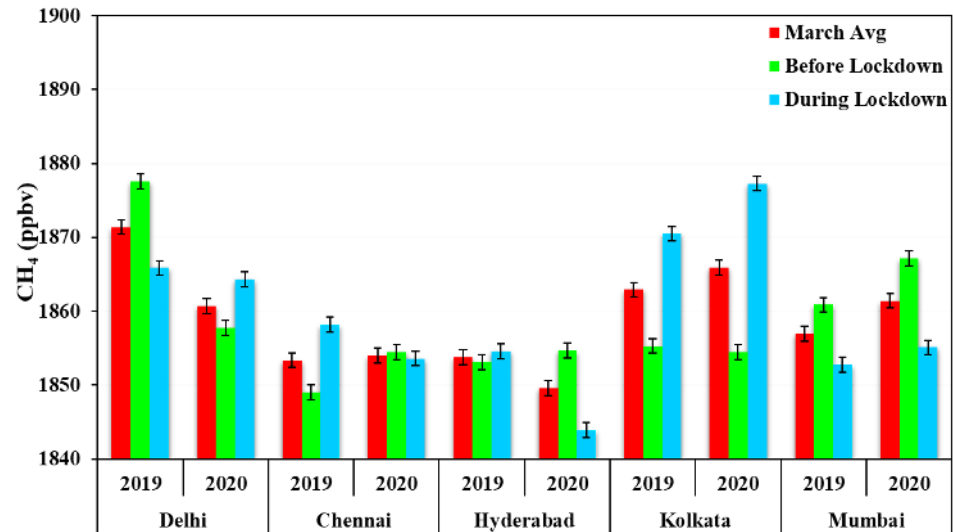
Fig. 9. Average methane concentrations at 925 hPa over five cities during (a) March (red bars); (b) before lockdown (10–21 March) (green bars) and (c) during lockdown (22–31 March) (blue bars).
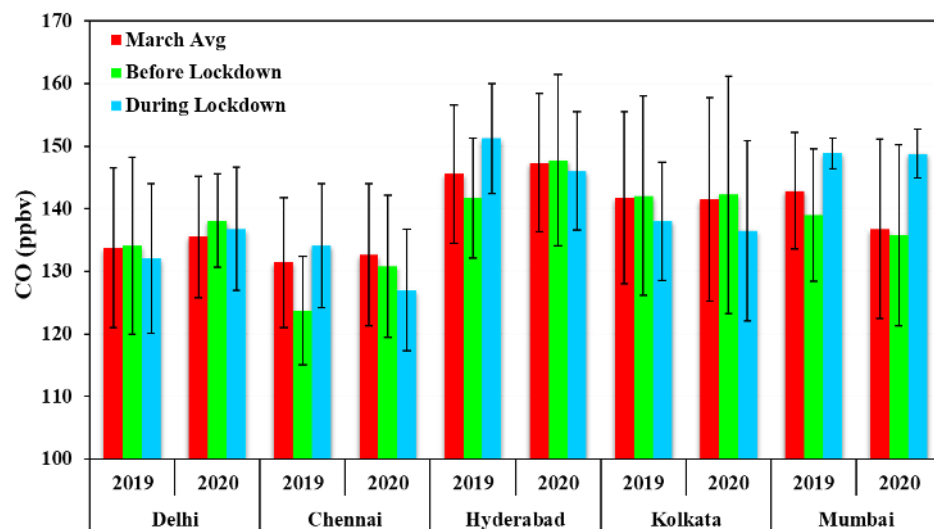

Fig. 10. Average CO at 925 hPa over five cities during (a) March (red bars); (b) before lockdown (green bars) and (c) during lockdown (blue bars).

2019 and sudden decline in CO concentration during lockdown period. In Mumbai, an increase in CO concentration during lockdown period.

The effect of the lockdown was observed over the ozone concentration at the pressure level 925 hPa close to the surface (Fig. 11). In Delhi, decline in Ozone concentration up to 6.93% during 22–31 March 2020, whereas, during similar days, an increase of 2.33% in Delhi was observed. In Kolkata and Mumbai, there is an enhancement of 1.81% and 0.24%, respectively during 22–31 March 2020 but Chennai and Hyderabad show rise in Ozone concentration of .87% and .11%. On comparing 2019 and 2020 results, the average concentration is observed to be higher in Delhi, Kolkata and Mumbai but Hyderabad and Chennai a slight increase in 2020 was observed compared to 2019. Atmospheric chemistry and meteorology play quite important role over Chennai and Hyderabad, we observe rise in HCHO concentration due to higher temperature in comparison to other cities that may play role in enhancement in slight enhancement in ozone concentration. Also, we found time lag in methane and ozone concentrations. The increase in CH_4 concentration during 10–21 March, is likely to cause rise in ozone concentration during 22–31 March. But no
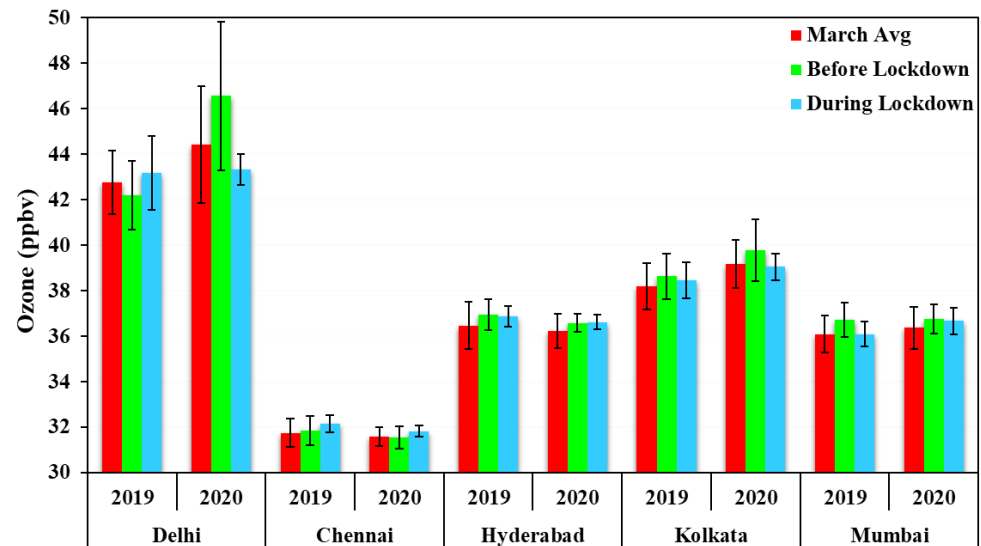
Fig. 11. Average Ozone at 925 hPa over five cities during (a) March (red bars); (b) before lockdown (green bars) and (c) during lockdown (blue bars).

time lag is observed over Mumbai, as higher ozone concentration with higher CH_4 concentration. But no direct correlation is observed in CO and ozone concertation.

These results show pronounced changes in concentration of various gases during lockdown period over India due to decline in anthropogenic activities and change in meteorology. Our results during lockdown periods will be useful to the atmospheric modelling and climate community to evaluate radiative budget and long-term changes in India and over Asian countries.

3 CONCLUSION

During lockdown, major sources of atmospheric pollutants were either completely closed or partially open, thus, pronounced changes in various trace gases (HCHO, NO_2, SO_2, CH_4 and CO) were observed. During lockdown, natural source along with few anthropogenic activities like crop burning, power plants played an important role. In Delhi, Kolkata, Mumbai, and Hyderabad sudden decline in $PM_{2.5}$ concentration was observed. But no major changes were observed in Chennai. HCHO concentration was decreased in major parts of India but the enhancement in temperature helped in rising HCHO concentration in the southern and eastern parts of India. The tropospheric NO_2 was seen to be decreased at Delhi, Mumbai, Kolkata, and Chennai during lockdown period and it is lower than those in 2019. Over Hyderabad no decline is observed during 2020 but average NO_2 concertation in 2020 is observed to be lower compared to 2019 during lockdown period. Decline in total column SO_2 was observed in major parts of India but Rajasthan and Punjab region (the north western parts) show some enhancement due to long range transport of airmass from Pakistan region. Some of the areas show enhancement in the concentration due to the crop residue burning and dust events. Similarly, we observed change in concentration in CH_4, CO and ozone during lockdown period and but methane concentration show no pronounced changes due to its longer residential time in atmosphere. The CO concentration is also affected by the anthropogenic activity and decline is observed during lockdown period. We observed a time lag in ozone and CH_4 concentration at the pressure level 925 hPa over these cities as higher CH_4 before the 21 March caused higher ozone concentration after 21 March. These results show that these trace gases are not only depended over the anthropogenic activities, but also dependent on natural processes and long-range transport and the winds play an important role in bringing pollutants from the rural areas to metro cities. Among all the major pollutants, particulate matter concentration and NO_2 show the most significant decline in India during lockdown. SO_2 and CO show moderate decline but due to some influential factors like crop residue burning, dust and long-range transport of pollutants from neighbouring countries, the decline is comparatively lesser in NO_2.

Similarly, CH_4 and O_3 are also influenced by the lockdown due to lesser anthropogenic emissions but these changes are less significant due to their longer resident time and influenced by secondary pollutants.

ADDITIONAL INFORMATION

Authorship Contribution Statement

Ramesh P Singh: Conceptualization and writing review and editing, **Akshansha Chauhan:** Data curation, Software, original draft, Writing and finalization of manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

All the data used in the present study are freely available through NASA Giovanni portal; if needed, we will provide the data used in the present study to anyone.

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